

PHOTOPRODUCTION OF HEAVY VECTOR MESONS AT HERA – A TESTFIELD FOR DIFFRACTION [◊]

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Abstract

Exclusive diffractive photoproduction of heavy vector mesons ($V=\phi, J/\psi$ and Υ) at HERA is studied in a model employing a dipole Pomeron exchange (P) with an inelastic γPV vertex. The model is fitted to the data on $d\sigma/dt$, B and σ_{el} for $Q^2 = 0$ and beyond the threshold region. The elastic cross sections for both ϕ and J/ψ photoproduction show a moderate increase within the HERA energy region. The flattening of the slope $B(s)$ (little or no shrinkage) for J/ψ is not correlated with the slope of the Pomeron trajectory. Estimates for Υ photoproduction at HERA are given.

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1. INTRODUCTION

Diffractive photoproduction, as well electroproduction, of heavy vector mesons at HERA continues attracting attention of both theorist and experimentalists (for a recent review see e.g. Refs. [1]- [3]; a comprehensive earlier review on this subject can be found in Ref. [4]) as a unique testfield for diffraction, an interface between "soft" and "hard" physics, with three independent kinematical variables, the c.m.s energy $W = \sqrt{s}$, the transferred momentum $\sqrt{-t}$ and the virtuality of the external particle(s) $Q^2 = -q^2$ involved simultaneously. High masses M_V of the external vector mesons are usually treated on the same footing as the photon virtuality, by introducing the variable $\tilde{Q}^2 = Q^2 + M_V^2$, although M_V^2 should not be identified with Q^2 . In the present paper we consider only photoproduction, i.e. $Q^2 = 0$.

An important reason why heavy vector mesons are particularly suitable to study diffraction is that, by the OZI rule [5], photoproduction of heavy vector mesons is mediated by the exchange of a Regge trajectory with vacuum quantum numbers and made of gluons (the Pomeron trajectory). In the case of the ϕ production, a small contribution from subleading, secondary Reggeons – due to the $\omega - \phi$ mixing is also possible.

Reactions and/or kinematical regions with the Pomeron dominance (Pomeron "filters") have been looked for long ago – e. g. in the elastic scattering with exotic direct channels (like in K^+p or pp scattering) or in other reactions (mainly $\bar{p}p$) at very high energies. In the hadron scattering, however, genuine Pomeron "filters" cannot be completely realized since even in the case of exotic channels a small contribution from secondary trajectories is inevitably present due to the breakdown of the exchange degeneracy. The alternative way to filter – by going to very high energies – is trapped by another (even less known) object – the Odderon

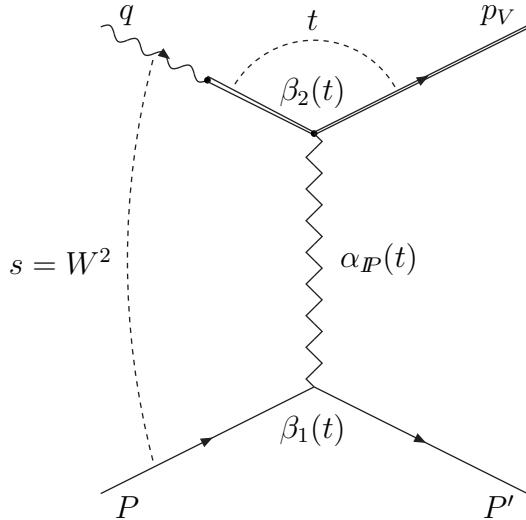


Figure 1: Elastic photoproduction according to Vector Meson Dominance

that obscures the picture and makes the discrimination ambiguous. In the case of photoproduction, only positive the C-parity exchange is allowed (the Odderon exchange is forbidden).

The application of the Regge pole theory to photoproduction usually implies also the validity of vector the meson dominance (VMD), by which the photon, before interacting with the proton by means of a Reggeon exchange, first fluctuates, becoming a vector meson (Fig 1). The applicability of VMD and its generalizations to heavy meson states have been recently discussed in a number of papers [6], [7].

An alternative to this typical Regge pole model of photoproduction, is perturbative QCD (pQCD). While (pQCD) calculations are efficient (see e.g. Refs. [8]-[12]) in the evaluation of the upper vertex of Fig. 2, or of the proton structure function probed by a "hard" Pomeron and related to the imaginary part of the photoproduction forward scattering , they are less appropriate for studying the

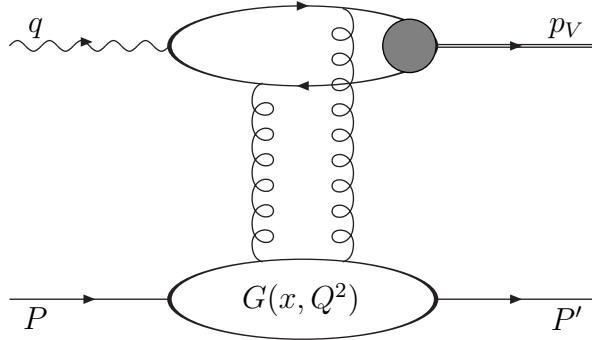


Figure 2: Elastic photoproduction according to perturbative QCD

typically non-perturbative features of diffraction, such as the t -dependence (shape of the assumed cone), the energy dependence of its slope, of the cross sections etc.

Recent studies [13] involve – apart from the abovementioned measurable quantities – also more subtle details, such as photoproduction of radially excited states, the helicity dependence etc. In a different paper [14] a detailed analysis of the t -dependence of the cone, including a possible dip-bump structure, seen in hadronic reactions was studied.

Most of the existing models rely on the so-called two-component picture, a compilation of the "soft" mechanism (see Fig. 1), essentially based on VMD and the Donnachie-Landshoff (DL) model of the Pomeron [15] and a "hard" one based on pQCD calculation of the exchange of a pair of gluons coupled to the quark-antiquark pair, as illustrated in Fig. 2, or the dipole picture [13] (not to be confused with the dipole Pomeron!), where the nonperturbative effects from the propagator are plugged into the vertices. Apart from the peculiarities of the different models, a common feature and main result of all these approaches is a power increase in energy of the cross sections s^ϵ , fed in from the DL model, the fitted value ϵ being

considered indicative of the "hardness" of diffraction. Another argument in favour of the "hardness" of diffraction at HERA, widely discussed now in literature [16] is the apparent flatness (small, or vanishing slope) of the Pomeron trajectory. Anticipating our forthcoming discussion, here we only notice that the Pomeron intercept is universal, independent of the virtuality or mass of the external particles, so the abovementioned effect may have a different origin.

The aim of the present paper is an analysis of the basic assumptions behind the existing models. To this end we use a factorized model with a Pomeron exchange combining Figs. 1 and 2, without specifying the details (VMD or pQCD) of the upper vertex. Instead, we consider a general form for the (inelastic) γPV vertex and a two-term Pomeron exchange (simple and double pole). By confronting the model with the data we study its physical consequences.

2. KINEMATICS AND THE HERA DATA

Here we introduce the kinematics and make several general comments concerning the HERA data, both from ZEUS and H1 collaborations.

We use the standard notation for the reaction energy (see Fig. 3). The square of the c.m.s. energy and the momentum transfer to the proton are, respectively,

$$W^2 = (q + P)^2 , \quad t = (P - P')^2 ,$$

being

$$| t |_{min} \approx m_p^2 \frac{(M_V^2 + Q^2)^2}{W^4} .$$

Here M_V is the vector-meson mass, m_p the proton mass and $Q^2 = -q^2$ is the photon

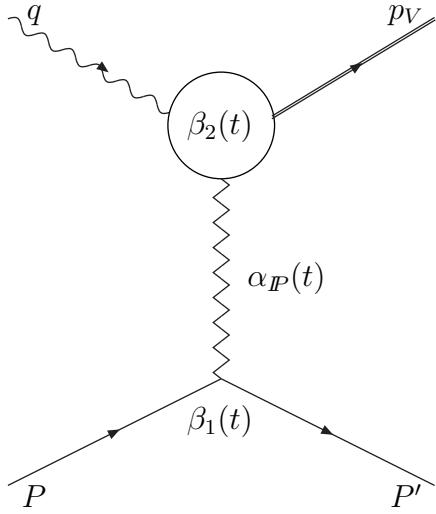


Figure 3: Elastic photoproduction with an inelastic γPV vertex. The wiggly line, showing the Pomeron exchange, corresponds to a sum of two diagrams, i.e. simple and double pole exchanges.

virtuality. In the following we will use the symbol s to indicate W^2 . At HERA one has $20 \text{ GeV} < W < 240 \text{ GeV}$, $-13 \text{ GeV}^2 < t < -|t|_{min}$, with $|t|_{min} \approx 10^{-4} \text{ GeV}$ negligibly small.

Since the differential cross section is the only directly observable quantity, σ_{el} , the slope B and other quantities being derivatives, its determination and interpretation is of great importance; small errors in $d\sigma/dt$ may be amplified in σ_{el} or in B . It should be admitted that the precision of the data is inferior to those in elastic hadron scattering. Therefore, in studying universal diffractive phenomena (such as the shape of the cone) or parameters (e.g. of the Pomeron trajectory) one should rely on the existing experience in hadronic (e.g. pp or $\bar{p}p$) scattering at high energies. In particular, two unmistakable structures superimposed on the nearly exponential cone are known to exist (see e.g. Refs. [17], [18]):

1. The "break", or changes of the local slope at $t \approx -0.1 \text{ GeV}^2$, due to the nearby 2-pion threshold in the unphysical region ($t > 0$), resulting in the sharpening of the cone (increase of $B(t)$ towards $t = 0$). This tiny effect is not yet observable at the level of statistics typical of the HERA measurements.
2. The dip-bump structure, clearly seen and thoroughly studied [17] in hadronic reaction, is highly indicative of the diffractive phenomena. Its position, in general, is determined [17] by the slope B and the amount of absorptions. While the smaller – with respect to the pp scattering – slope in the heavy vector meson production evidently pushes the dip outwards, the amount of absorptions is less known (it is expected to have a counter effect on the position of the dip). More data are needed to reveal the existence of a dip, which would be an important step towards a better understanding of diffraction.

The apparent flattening of the cone in J/ψ photoproduction may seem an indication of a nonlinear Pomeron trajectory. Here again the lesson from pp and $\bar{p}p$ scatterings may be useful. It tells us [17] that the slope of the Pomeron trajectory, apart from the small $|t|$ curvature due to the lightest two-pion threshold in the cross channel of the amplitude, remains almost constant until about 1 GeV^2 – the neighbourhood of the dip. The nonlinearity of the (Pomeron) trajectory can be of fundamental importance at large $|t|$, however the present HERA data are unlikely to tell us more about its details than the hadron scattering data do. Instead, the form of the nonlinear Pomeron trajectory gained from pp and $\bar{p}p$ data may be used in identifying new effects at HERA.

Given the abovementioned uncertainties, the formula

$$\sigma_{el} = \frac{1}{B_{exp}} \frac{d\sigma}{dt} \bigg|_{t=0},$$

where B_{exp} is the experimental value of the slope, may be the right approximation. Formally it implies $B(t = 0)$, although the slope can be determined only with respect to a finite interval (bin) in t . In view of the apparent flattening of the cone and the uncertainties in the determination of $d\sigma/dt$, the choice of the relevant bins and the resulting B strongly influences the calculated σ_{el} . A reasonable way [13] to account for the above-mentioned effect of the "sharpening" of $d\sigma/dt$ towards $t = 0$, is by augmenting the measured B by 1 or 2 units of GeV^2 . Since the determination of B is crucial for the dynamics of J/ψ production (see Fig. 4 and below), this point needs further clarification.

3. DIFFRACTION AND REGGE POLE MODELS

Factorization is a basic ingredient of any Regge pole model (see Ref. [19]). Accordingly, the scattering amplitude corresponding to a simple Regge pole exchange, up a signature factor $\xi(t)$, is a product of two vertices $\beta_1(t)$, $\beta_2(t)$ and a "propagator" $(s/s_0)^{\alpha(t)}$ (see Fig. 1). If the amplitude is a sum of several exchanges (the Pomeron itself may be more than just a simple pole!), then each term conserves its factorization properties separately.

The lower vertex in Fig. 1 is well known (from the pp and $\bar{p}p$ scattering) to be e^{bt} (the application of more involved forms is not relevant here), an estimate for b being [19] $b = 2.25\ GeV^{-2}$. By factorization, the properties and values of the parameters in the Pomeron trajectory are universal and reaction-independent. Below we use the "canonical" value of $\alpha' = 0.25\ GeV^{-2}$ for the Pomeron slope.

This input is sufficient to calculate the slope of the exponential cone

$$B(s) = \frac{d}{dt} \ln \frac{d\sigma}{dt} \Big|_{t=0} .$$

As a result, for the extreme case of a point-like coupling in the upper vertex, $b_2 = 0$:

$$B(s) = (4.5 + 0.5 \ln(s/s_0)) \text{ GeV}^{-2} , \quad (1)$$

and one gets $B = 8.75 \text{ GeV}^{-2}$ at $W = 70 \text{ GeV}$ (with $s_0 = 1 \text{ GeV}^2$) – much too much compared to the data. This value can be lowered by: lowering b [20] and [21] (difficult, since the above value is already a conservative estimate!), lowering α' (incompatible with factorization) and/or increasing s_0 . The last option is acceptable, moreover demanded by the data on the hadron scattering [17],[18], although in the relevant fits the increase of s_0 is accompanied by a corresponding increase of b , the net effect for B , eq (1), remains nearly zero. Anyway, even the lower limit of B according to Eq. (1), $B = 4.5 \text{ GeV}^{-2}$, saturates the experimental value for the J/ψ photoproduction (see Fig. 4). In other words, in the simple Regge pole model, there is no room left for the radius of a vector meson as heavy as J/ψ or Υ .

The next important issue is whether the Pomeron contribution can be adequately represented by a single pole exchange – as it is in the case in the DL model. If so, the total cross section is simply $\sigma_t \sim s^\epsilon$ and the elastic cross section is also a single power, $\sigma_{el} \sim s^\epsilon$.

The original DL model was always fitted to the data with two terms, the "Pomeron" and an effective contribution of subleading Reggeons. The latter effectively contains also the low energy background (although this was never emphasized). The increasing part of the Pomeron should be added by a constant background - as it follows from the empirical fits to the total cross sections [23],

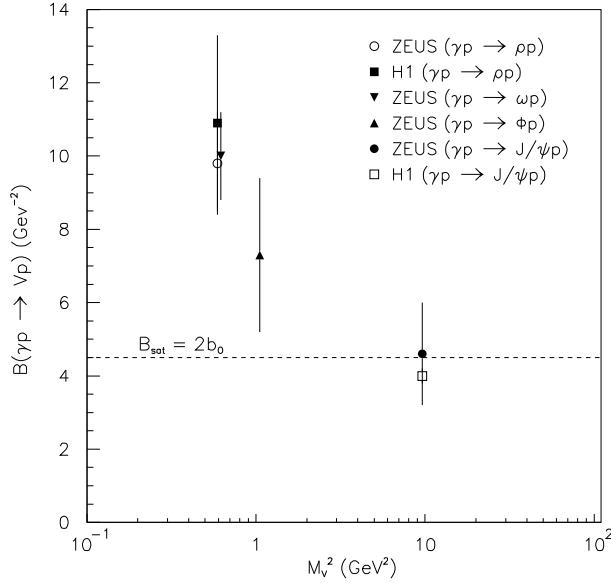


Figure 4: The slope B versus the square M_V^2 of the mass of Vector Bosons. Existing experimental data converge, saturating at the minimal value given by the lower pPp vertex, $B = 4.5 \text{ GeV}^{-2}$.

[18], [24], structure functions and their evolution [25] or from non-perturbative QCD calculations [26].

To illustrate the aforesaid, let us write the Regge dipole scattering amplitude in a simple "geometrical" form (see [17]):

$$A(s, t) \sim R^2 e^{R^2 t},$$

where $R^2 \equiv R^2(s) = \alpha'(b + L - i\pi/2)$, $L \equiv \ln(\frac{s}{s_0})$. The total cross section in this model is

$$\sigma_t \sim b + L,$$

while the elastic cross section grows as

$$\sigma_{el} \sim \frac{(b + L)^2 + \pi^2/4}{b + L}$$

and its asymptotics is delayed with respect to a single rising term (be it a power or logarithm(s)). By this simple example (anticipating a more realistic model to be presented in the next section), we intend to demonstrate the important role of a constant background to the rising term (whatever its form), and that the parametrizations of the HERA data by a single power W^ϵ may be oversimplified.

4. DIPOLE POMERON MODEL OF DIFFRACTION AT HERA

We consider the reaction $\gamma p \rightarrow Vp$, where V stands for ϕ , J/ψ or Υ , in the framework of the Regge pole model with a dipole Pomeron (DP for brevity) exchange in the t channel and inelastic γPV upper vertex shown in Fig. 3.

In the angular momentum plane, the partial wave amplitude corresponding to a Regge dipole is

$$a(j, t) = \frac{\beta(j, t)}{[j - \alpha(t)]^2} = \frac{d}{d\alpha(t)} \frac{\beta(j, t)}{j - \alpha(t)},$$

where the function $\beta(j)$ is t -independent and non-singular at $j = \alpha(t)$.

The above derivative automatically produces a $\ln s$ term in the scattering amplitude, providing thus for rising cross sections with Pomeron intercept equal to one, securing the unitarity bounds. Let us notice also that within Regge type models, this is the fastest rise allowed by unitarity, since asymptotically $\sigma_t \leq B$ and the maximally allowed shrinkage here is $B \sim \ln s$.

The DP model was successively applied to hadronic reactions in describing both the s - and t -dependence (for a review of the DP model see [17]). Around $W \sim 100$ GeV the rate of increase of the cross sections numerically is close to that

in the DL model, i.e. $\sim W^{2\epsilon}$, with $\epsilon \approx 0.08$, but conceptually they are quite different. Furthermore, the interference between two terms, that can be interpreted as contributions from a simple and a double pole produces a diffractive pattern in t , confirmed experimentally in hadronic reactions (see Refs. [17], [18]).

In what follows we apply the above concept to diffractive photoproduction of heavy mesons. Neglecting the spin, we write the invariant scattering amplitude corresponding to the exchange of a DP as

$$A(s, t) = i(-is/s_0)^{\alpha(t)-1} \{G_1(t) + G_2(t)[\ln(s/s_0) - i\pi/2]\} , \quad (2)$$

where

$$G_1(t) = A_1 e^{bt} (1 + h_1 t) \quad (3)$$

and

$$G_2(t) = A_2 e^{bt} (1 + h_2 t) - \gamma \quad (4)$$

are the residua of the simple and double pole, respectively. $G_1(t)$ factorizes (see, for instance, Fig. 3) into a standard pPp vertex $\sim e^{bt}$, with $b = 2.25 \text{ GeV}^{-2}$ determined from the pp scattering, and the γPV vertex, that we parametrize by a simple polynomial with a free parameter h_1 to be fitted to the data. Were VMD applicable to the upper vertex, one should expect h_1 to be small and positive (expansion of an exponential with a small slope (radius)). If however, h_1 turns out to be negative, this will indicate departure from VMD with an increase of the upper vertex in $|t|$.

The residue of the double pole $G_2(t)$ may be cast from $G_1(t)$ by an integration (see [17]). Here we relax this rather stringent constrain that relates the values of A_2 to h_2 and A_1 to h_1 , respectively, keeping only the integration constant γ as another free parameter. If that relation will be confirmed by the data, it will be indicative of the hadronic nature of diffraction in photoproduction.

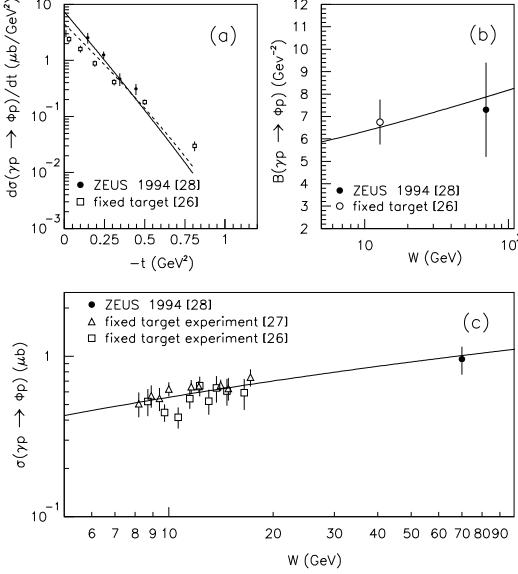


Figure 5: ϕ photoproduction: a) the differential cross section: the dotted line corresponds to the average energy $W = 13.3$ GeV while the full line to the average energy 70 GeV ; b) the slope parameter; c) the elastic cross section. The data are taken from Refs. [27], [28] and [29].

We use a simple linear trajectory for the Pomeron $\alpha(t) = 1 + 0.25t$. This linear trajectory may be replaced by a nonlinear one in future, more sophisticated fits to the data.

From Eq. (1) we get for the elastic differential cross section

$$\frac{d\sigma}{dt} = (s/s_0)^{2\alpha(t)-2} [(G_1(t) + G_2(t) \ln(s/s_0))^2 + \frac{\pi^2}{4} G_2^2(t)]. \quad (5)$$

whence σ_{el} is calculated according to (see Sec. 2):

$$\sigma_{el} = \frac{1}{B} \frac{d\sigma}{dt} \bigg|_{t=0}. \quad (6)$$

The s and t -dependence of the slope B can be calculated from

$$B(s, t) = \frac{d}{dt} \left(\ln \frac{d\sigma}{dt} \right) \bigg|_{t=0} = 2\alpha' \ln(s/s_0) + N/D, \quad (7)$$

where

$$N = 2 \left([A_1 + (A_2 - \gamma) \ln(s/s_0)] [A_1(b+h_1) + A_2(b+h_2) \ln(s/s_0)] + \frac{\pi^2}{4} (A_2 - \gamma) A_2(b+h_2) \right)$$

and

$$D = \frac{d\sigma}{dt} \Big|_{t=0} = [A_1 + (A_2 - \gamma) \ln(s/s_0)]^2 + \frac{\pi^2}{4} (A_2 - \gamma)^2.$$

In calculating σ_{el} however we shall use the experimental value of the slope B_{exp} .

5. FITS TO THE HERA DATA: DISCUSSION OF THE RESULTS

To study the Pomeron behaviour alone, unbiased by possible threshold effects, we impose a lower bound in energy, $W > 8 \text{ GeV}$ in the case of the ϕ photoproduction and $W > 30 \text{ GeV}$ in the case of the J/ψ photoproduction. As mentioned, here we consider only the case $Q^2 = 0$.

The parameters to be fitted are A_1, A_2, h_1, h_2 and γ .

Figs. 5 a) – c) show the differential and the integrated elastic cross sections as well as the slope parameter of the ϕ production fitted to the fixed target [27], [28] and the HERA collider [29] data. The values of the fitted parameters turn out to be $A_1 = 1.9126 \mu b$, $A_2 = 0.18203 \mu b$, $h_1 = 0.85842 \text{ GeV}^{-2}$, $h_2 = 0$ and $s_0 = (8 \text{ GeV})^2$.

Figs. 6 a – c) show the same quantities for the J/ψ photoproduction, with the fitted parameters: $A_1 = 0.27523 \mu b$, $A_2 = 0.091278 \mu b$, $h_1 = -0.80606 \text{ GeV}^{-2}$, $h_2 = 0$ and $s_0 = (30 \text{ GeV})^2$. Here only the HERA data [29] – [31] were used to fit the parameters.

The following comments are here in order

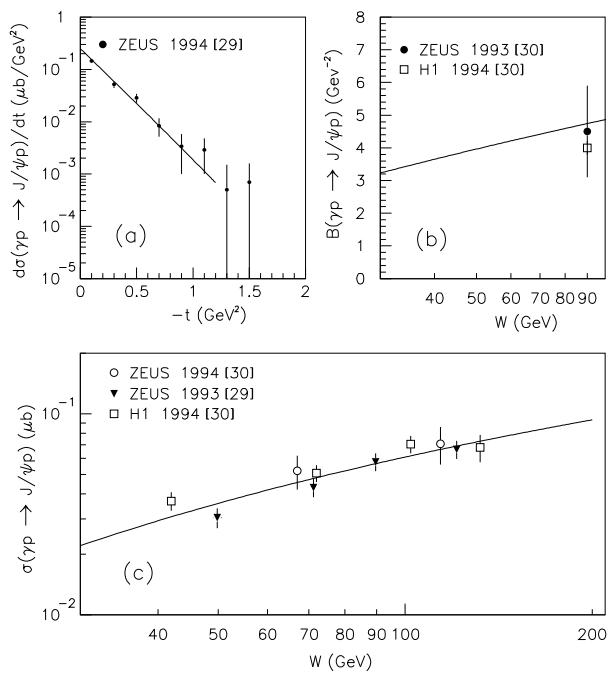


Figure 6: J/ψ photoproduction: a) the differential cross section; b) the slope parameter; c) the elastic cross section. The data are taken from Refs. [29], [30] and [31].

Throughout the fitting procedure γ remains very small so, in order to reduce the number of the free parameters, we simple set $\gamma = 0$. Since this parameter determines the amount of absorptions (present in the model, see Ref. [17]) and the fate of a possible dip, this simplification is to be relaxed after a better understanding of the present approach (from the previous experience in hadronic scattering [17], [18], γ is known to be small anyway).

Photoproduction of J/ψ requires the parameter h_1 to be negative. This is the effect of the "saturation" of the slope by the lower vertex only, visible in Fig. 4. To meet the data, the upper, inelastic vertex "subtracts" from the net slope. A negative value of h does not favour VMD, indicating a more complicated, inelastic structure in the upper vertex of Fig. 3.

We notice also that reasonable fits require large values of s_0 , increasing with the mass of the produced vector meson. This parameter is correlated in some way with the external masses. Large values of $s_0 \sim 100 \text{ GeV}^2$ are typical also for the hadronic reactions [17], [18], [33], [34].

Let us now discuss some general features in the behaviour of the observables, as they follow from our model.

Even though we use a linear Pomeron trajectory, the cone is not exactly exponential due to the interference of the two terms of the Pomeron. An important immediate consequence is that the apparent non-shrinkage (little or no s -dependence in B) in the case of J/ψ may result from the interference of the simple and double poles. Otherwise stated, the form

$$\frac{d\sigma}{dt} = f(t)W^{[4\alpha(t)-4]}, \quad (8)$$

used in Ref. [16] to fit the Pomeron trajectory and resulting in its apparent flatness,

$\alpha' \approx 0$, is not unique (e.g. f may depend also on s). The flattening of $B(s)$, visible in Fig. 6 c), can be achieved with a universal Pomeron intercept, $\alpha' = 0.25 \text{ GeV}^{-2}$ if e.g. (5) is used instead of (8). Moreover, the flattening of the slope may be followed by an "antishrinkage" in Υ production (the negative, albeit small value of α' in [16] could be a message of this trend).

The energy dependence of the elastic cross sections, shown in Figs. 5 a) and 6 a), is mild and fits the data perfectly well. The large mass of J/ψ does not "harden" the dynamics, i.e. the rate of increase is similar to the case of its lighter counterpart ϕ . Moreover, the present increase corresponds to a transitory regime, preceding the asymptotic $\sim \ln s$ rise, to set up at still higher energies.

To make predictions, we try to establish regularities between the values of the fitted parameters. Since the radius of the heavier Υ is smaller than that of J/ψ , which is already near, or even below the "saturation" value (see Fig. 4), the effect of the "subtraction" (negative value of h_1) in the case of Υ is expected to be the same, or even weaker than in J/ψ . So it may be reasonable to choose $h_{1,2}$ to be the same as in J/ψ . The slope B in the Υ photoproduction is also expected to be equal (or even slightly larger than) the saturation value $\approx 4.5 \text{ GeV}^{-2}$. The parameter s_0 tends to rise as $\ln M_V^2$, so by extrapolation we choose $s_0 = (50 \text{ GeV})^2$ for Υ production.

The relative normalization scale between the cross sections for various vector mesons is determined mainly by the parameter A_1 and it can be estimated according to the formula

$$A \sim (m_q)^{-4} M_V \Gamma_{V \rightarrow e^+ e^-} (e)^2,$$

where M_V and m_q are the masses of the relevant vector mesons and the quark they contain, $\Gamma_{V \rightarrow e^+ e^-}$ is the decay width of the vector meson and e is the electric charge

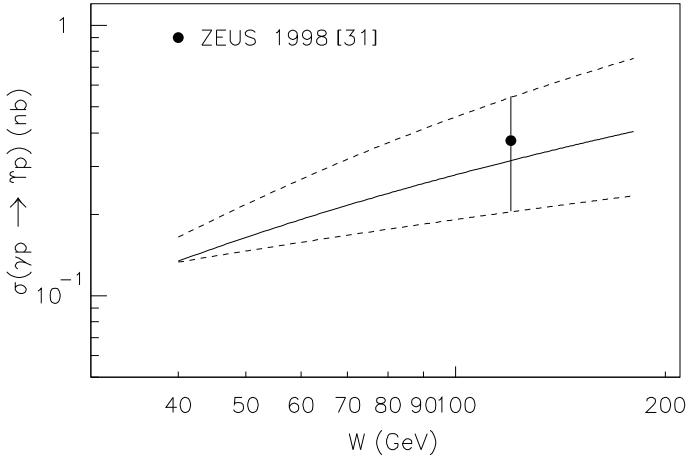


Figure 7: A prediction for the elastic Υ photoproduction. The data point is taken from Ref. [32].

of the relevant quark. It reproduces qualitatively the ratio between ϕ , J/ψ and Υ photoproduction. Since, however, the parameter A_2 also contributes to the relative scales, we better rely on the recently measured Υ photoproduction cross section [32] to fit these parameters.

Setting $\gamma = 0$, we adjust uniquely the normalization constant A_1 to the measured value [32] of σ_{el} in the Υ photoproduction and get 0.2 pb . The parameter A_2 , on the other hand shows more flexibility, by varying for fixed A_1 within the range $0.1 \leq A_2 \leq 0.37 \text{ pb}$, the central value being $A_2 = 0.2 \text{ pb}$. The predicted elastic cross section is shown in Fig. 7.

Finally, we note that the present fits – because of to the limited number of the data points relative to the number of the free parameters – should be considered as preliminary, aimed at an exploration of a dynamical mechanism of diffractive photoproduction, alternative to the existing ones. Further comparison with the data may result in a different set of the fitted parameters, although the general

features are expected to remain unchanged.

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